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On the Deep Circulation of the Greenland Sea - Revisited

by

Klaus Peter Koltermann

Deutsches
Hydrographisches Institut

Hamburg
Federal Republic of Germany

Abstract: A very extensive hydrographic and tracer data set for the Greenland and Norwegian Seas from 1982 to 1985 reveals new insights into the deep circulation of this area. Mainly driven by thermohaline processes, the transport of salt at depth occurs through narrow boundary currents. The basin topography has a great influence on potential pathways, giving way to inter-basin exchange of properties through gaps in or spilling over the Mohn-Knipovitch Ridges.

The Greenland Sea cyclonic gyre is decoupled at mid-depth, changing to an anti-cyclonic rotation close to the bottom. The transition layer is marked by the Deep Salinity Maximum at 1700 m. The Deep Arctic Ocean Outflow on the Greenland shelf break, the main salt input from the North at this depth, splits its path at ca. 77° N, clearly marking deep boundary currents at both sides of the basin. Depending on the seasonal deep convection signal in the Boreas Basin to the North, the Deep Arctic Outflow follows the Greenland Fracture Zone in a secondary salinity maximum.

Newly produced GSDW from the central gyre region marks a low salinity, high oxygen region in the deep salinity maximum layer. Beneath, the new GSDW is spread by the anti-cyclonic gyre and mixed at its periphery with the salty, nutrient-rich and low-oxygen Deep Arctic Outflow. This admixture is well documented in the southern Greenland Sea and finally leaves the basin as new NSDW.

Introduction: The Greenland Sea as the main production area for the fresh, very dense and well oxygenated Greenland Sea Deep Water GSDW with $\Theta \approx -1.266$ °C and $S \approx 34.892$ is dominated by the cyclonic Greenland Sea Gyre. Partly wind-driven, probably mostly density-driven it governs the circulation of the area: in the east warm and salty water of Atlantic origin is carried northward along Spitsbergen. Part of it enters the Arctic Ocean through Fram Strait, part of it is recirculated and feeds the sub-surface Return Atlantic

Current (RAC) along the East Greenland Shelf. On its inshore side, the cold and fresh waters of the East Greenland Current provide a major heat sink. This circulation is mostly confined to the top 500 m. Below, density gradients are minimal as salinity and temperature signals get very small. To separate the upper from the lower layers, the density surface σ_1 = 32.785 has been chosen.

The data: The data used in this analysis were collected within the ICES - coordinated 'Deep Water Project': The Canadian RV 'Hudson' worked the area in Feburary to April 1982 (SIO,1984a,b), 'Meteor' in May to July 1982 (ANON,1986) followed by 'Polarstern' in July and August 1984 in Fram Strait. Details of the data sampling, qualities and methods are given in the reports.

The two layer system : The topography of the surface σ_1 = 32.785 (fig.1) shows a great vertical variance. From >1300 m depth in the Lofoten Basin it rises across the Mohn Ridge to < 100 m in the Greenland Sea. To the north it sinks again to ca. 500 m in the Boreas Basin and ca. 1000 m in Fram Strait. The sharpest horizontal gradients are found across the Mohn-Knipovitch Ridges that separate the Greenland from the Lofoten Basin. The salinity distribution (fig.2) shows essentially the same contours with a salinity minimum in the central gyre region. To maintain density, this minimum in salinity is compensated by very low temperatures of < -1.2 °C in the centre of the gyre (fig.3). To the north-west of the gyre we note warmer and salty water from the Greenland Shelf entering the Greenland and the Boreas Basin at ca. 800 m depth.

The isopycnal σ_2 = 37.457 defines the deep waters (AAGAARD et al.,1985) which do not leave the North Polar Seas: to the south the Greenland - Scotland Ridge prevents waters of this density to leave the system, in the North it can only spread as far as the Lomonossov Ridge. Thus this surface marks the upper limits of the deep water complex. In fig.(4) we find a similar topography as for the σ_1 = 32.785 surface. The dome of the Greenland Gyre rises on this surface to < 1300 m, whereas the anti-cyclonic gyre in the Lofoten Basin presses the surface down to about 3000 m. Both surfaces suggest a mainly barotropic flow in these basins following topography. The distribution of salinity on the σ_2-surface (fig.5) shows a well defined minimum in the centre of the gyre with S < 34.89 and temperatures below -1.2 °C, fig.(6). Both distributions indicate also some important features of the deep circulation, assuming isopycnal transports at these depths. While the minima are well confined to the abyssal plain of the Greenland Basin, GSDW with the centre characteristics of low salinity and low temperatures spreads east across the southern tip of the Greenland Fracture Zone (GFZ) and almost to the Knipovitch-Ridge. Another part of it flows across the GFZ into the Boreas Basin and a large excursion of the isotherms and isohalines denotes a southward transport from the gyre to Jan Mayen along the western side of the ridges. Only at 72° N and at 76° N an increase of salinities to > 34.909 and temperatures > -1.03 °C shows a cross-ridge advection of NSDW into the Greenland Basin.

Following the down-stream gradients in the Arctic Outflow and, where-ever obtainable, the manifestations of other deep boundary currents, we found strong evidence of a circulation that was rotating opposite to the one known for the upper gyre.

<u>The layers of extrema :</u> The deeper parts of the Greenland and Norwegian Seas are further structurized by a deep oxygen minimum at 1100 - 1300 m and a deep salinity maximum at 1600 to 1800 m depth. Both extrema can be noted in fig.(7) and fig.(8), where on a west-east section through the centre of the Greenland Basin salinity and oxygen is given. The dotted line in fig.(7) gives the depth of the oxygen minimum. One notes that both for the Greenland Basin and the Lofoten Basin oxygen concentrations decrease down to that depth and increase again further to bottom. In the Greenland Basin low oxygen waters spread from the western respective eastern sides into the basin, but essentially the minimum is maintained by 'upwelling' of fresher, colder and more oxygenated waters from below. The Deep Salinity Maximum at more than 1600 m depth is fed by the Deep Arctic Outflow in the west, carrying AODW/EBDW Deep Water with high salinities and temperatures ($\Theta \approx -0.96\,^{\circ}C$, $S \approx 34.92$) and low oxygen southward along the Greenland Shelf break at 1600 m depth on the isopycnal $\sigma_1 = 32.82$ (KOLTERMANN, 1985), and the spillover of saline water from intermediate depths in the Lofoten Basin. This salt flux is maintained by cross-isopycnal transport, a major supply mechanism from the intermediate depths of the Lofoten Basin, where the strong Atlantic Inflow carries salt northward. On the western side of the Ridges, this water of high salinities and silicate is carried away by deep narrow boundary currents.

All distributions indicate that the advective transport of salt at the deep maximum layer has been broken up at the centre of the gyre by convective processes that have carried low saline, cold and oxygen-rich waters down from upper layers. This assumption is further substantiated by mapping the salinities on the Deep Salinity Maximum (fig.9) and the oxygen concentrations on the Deep Oxygen Minimum (fig.10). Although both layers are separated by some 500 m in the centre of the gyre, they show the expected salinity minimum with $S < 34.895$ and oxygen maximum of $O_2 > 7.2$ ml/l. So the region where convective transfer of properties from upper and intermediate layers has occurred, is confined to an area of < 100 km diameter.

In the property distribution in the deep layers of the Greenland Sea we find

- an area of minimum salinities, high oxygen and low temperatures and silicate confined to the abyssal plain of the basin,
- increasing horizontal gradients. To the north and west they closely follow the topography, in the southern and eastern parts of the basin, especially over the rough topography, salinities, temperatures and silicate smoothly increase with decreasing oxygen concentrations,
- indications of an anti-cyclonic rotation in the deep layer.

Although the different suggested production processes (CARMACK, 1972, KILLWORTH, 1979, CLARKE et al., 1983, GASCARD et al., 1983, McDOUGALL (1983) for Deep Water in the Greenland Sea have so far never been observed or quantitatively assessed, the result of these processes, the low saline, cold and oxygen-rich GSDW, is well documented. The production in this area is linked into a chain of different interdepending processes that add density either by cooling and/or salt supply in different depths. The final triggering at the surface can well be done by convection processes down to 500 - 600 m. Brine release through even minimal sea-ice formation (CLARKE,1986) in the region with very low vertical stability and additional salt supply from the Deep Salinity Maximum can result in a complete vertical cascade transferring dense water to the bottom. GILL et al. (1979) suggest to look, instead of arguing on thermodynamical details of the processes, at the consequences of what, in a bulk assumption, is a net transfer of mass. Using their model appropriately scaled, it is explaining most of the observed features on the deep distribution of properties.

The Gill et al. model: Taking two superposed layers of different but homogeneous density, the effects of cooling of the upper layer are simulated by mass transfer from the upper to the lower layer. The model case tested for the field data uses a rigid lid approximation and friction, where the case with a mass transfer region of a radius of 0.7 relative units, scaled appropriately for the Greenland Sea, agreed with the length scales found in the data. The model predicts the flow field for the case of the mass transfer being confined to a limited region. The main features are

- doming of the interface to maintain pressure gradients in balance with the velocity field,

- cyclonic rotation of the upper layer due to conservation of angular momentum of particles that are drawn into the sink, but anti-cyclonic vorticity for the particles outside the mass transfer region due to shrinking of the vortex lines drawn up on the dome,

- anti-cyclonic rotation in the lower layer due to particles maintaining their angular momentum when pushed out from the mass transfer region, with some cyclonic rotation near the centre of mass transfer due to momentum transfer from the upper layer.

Fig.(11) is a conceptual sketch of the Gill et al. model. The rotation of the upper layer is shown by broken lines, the arrows give the horizontal tangential velocity profile. The thin circles indicate the sense of relative vorticity at the position of the circle, plus indicating cyclonic, minus anti-cyclonic vorticity. The dotted circle marks the limits of the mass transfer region for this case, corresponding to 0.7 relative units. This here was chosen to be equivalent to the diameter of the low salinity, high oxygen regions in the extrema layers. For the lower layer the bold lines and arrows indicate the velocity profile, with a cyclonic rotation within and an anti-cyclonic rotation outside the mass transfer region. The bold circles, again, indicate the respective vorticity.

For our case this model implies, that this mechanism transfers water with higher density from the upper layer within the mass transfer region to the lower layer. Outside this region the anti-cyclonic deep gyre redistributes the water. With the mass transfer region of < 100 km centred at the extrema regions, the model circulation scales fit into the abyssal Greenland Basin plain.

The Deep Gyre : The topographical constraints of the Greenland Shelf to the west and the Greenland Fracture Zone to the North are also guiding the Deep Arctic Outflow, which now adds low-oxygen, saline and silicate-rich water to the periphery of the deep gyre. The model geometry has been plotted into the topography (fig.12), where the bold arrows mark the cyclonic deep mass transfer region, the solid thin arrows the maximum anti-cyclonic speeds and the dotted arrows the 10% speed limit. The Deep Arctic Ocean Outflow follows the topography along the path indicated by the dotted, bi-furcating line. The existence of the Outflow has been verified by data south to the indicated positions of the arrow heads. Property correlations confirm the AODW contribution to the deep water masses found further south in the Greenland Sea Basin. Also shown are the main transport regions of GSDW from the Greenland Basin north to Fram Strait and east across the Knipovitch Ridge, and NSDW into the Greenland Basin. For the dotted area in the southwestern part of the Greenland basin, an increase in salinity and silicate, and a coinciding deep salinity maximum with the deep oxygen minimum suggest this area for a slow but continuous mixing of newly produced GSDW and AODW/EBDW to form pre-NSDW with $\Theta \approx -1.02$ C and $S \approx 34.909$. The few available data in this region show, besides southward increasing horizontal gradients, little variation in the vertical property profiles below 1600 m depth. The circulation scheme of the deep gyre of (fig.12) has been projected onto the salinity distribution on the Deep Salinity Maximum (fig.13) and the oxygen distribution on the Deep Oxygen Minimum. Both figures confirm the proposed mechanism to change the property fields of the abyssal Greenland Sea in a consistent pattern.

The main outflow of ca. 0.9 Sv of pre-NSDW, as measured with current-meters in 1982, occurs in the Jan Mayen Fracture Zone. This agrees well with published transports from box models, as SMETHIE et al.(1986) with 0.9 to 1.47 Sv or HEINZE (1986) with 1.19 (0.58 - 2.33) Sv for the total NSDW transport.

Conclusions: The cyclonic gyre known to dominate the Greenland Sea is confined to the top 1700 m. At greater depth high quality data suggest a different dynamical regime, mainly driven by mass transfer in an area of deep convective processes. The upper gyre subsequently is mainly driven by thermohaline forcing, less by variations in the wind-stress field. The horizontal changes in the position of the gyre apex from winter to summer, as noted by CARMACK (1972) may well depend on the deep convection in winter, which in turn depends on the ice edge position and the history of the local cooling of the surface layer, and the transition to a more wind-driven gyre in summer.

The two gyre system proposed by GILL et al.(1979) explains the deep circulation of the Greenland Sea Basin, as analyzed from high quality hydrography, nutrient and tracer data in the early 1980's. The anti-cyclonic gyre redistributes the newly formed GSDW laterally. At its periphery it mixes with the ambient water masses, which are clearly marked by saline, warmer contributions from the Deep Arctic Ocean Outflow. In the southern Greenland Sea this leads to the formation of 'almost' NSDW, which very closely anticipates already in Θ/S space the signature of the NSDW outflow at Jan Mayen.

The Deep Salinity Maximum and the Deep Oxygen Minimum provide indications of the possible transition layer between the two gyre systems. Further efforts are needed to fully understand the physics of this system, i.e. the role of the cross-ridge advection of intermediate waters from the Lofoten Basin. Vertical profiles of current velocity would be valuable, especially to calibrate geostrophical calculations. Also the seasonal or interannual changes regional convective events might have on this circulation scheme are of great importance.

With respect to the origin of water masses and their modification, the southwestern half of the Greenland Sea Basin below 1600 m depth carries many indications, for lack of adequate data coverage, of being the main production area of NSDW south of 75 °N.

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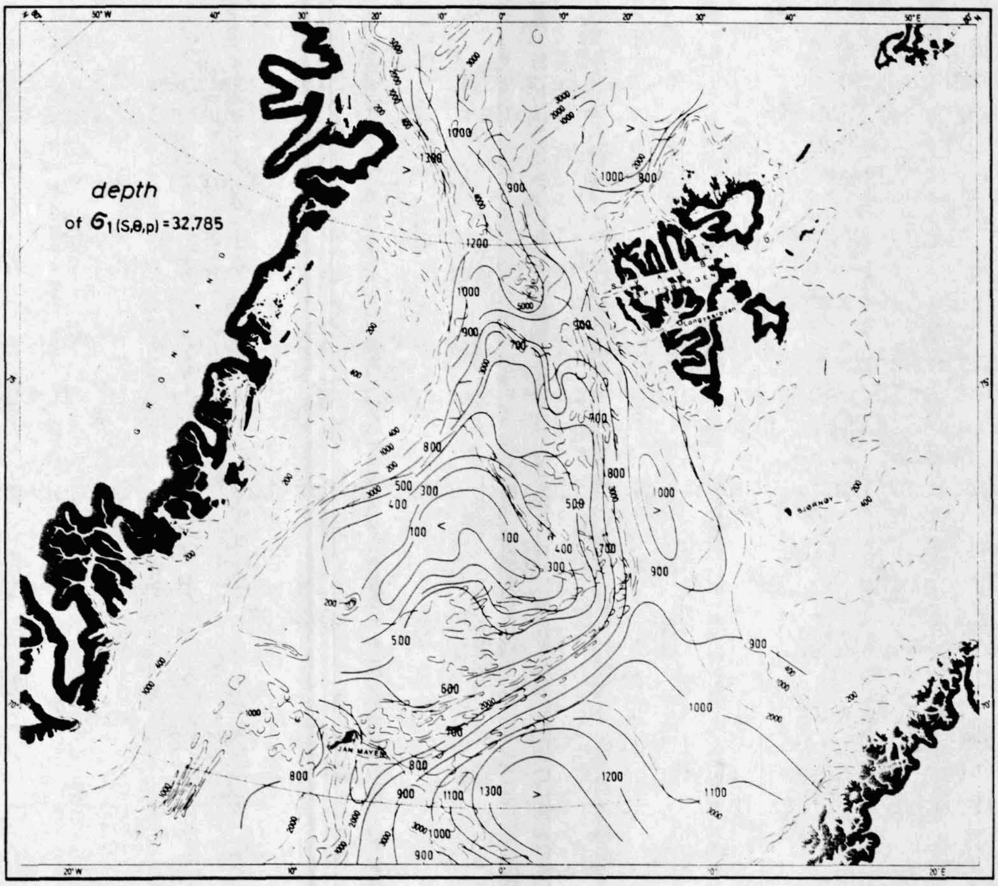

Fig.(1) The depth of the isopycnal $\sigma_1 = 32.785$

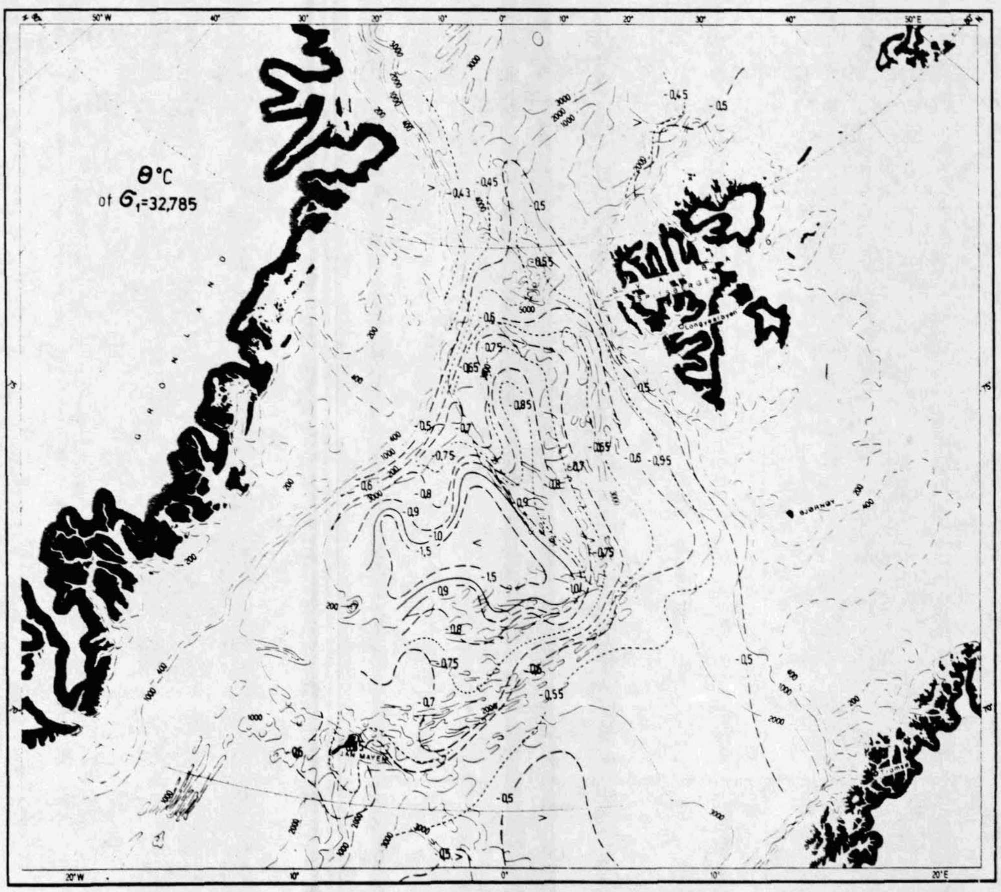

Fig.(2) The distribution of pot. temperature on the isopycnal $\sigma_1 = 32.785$

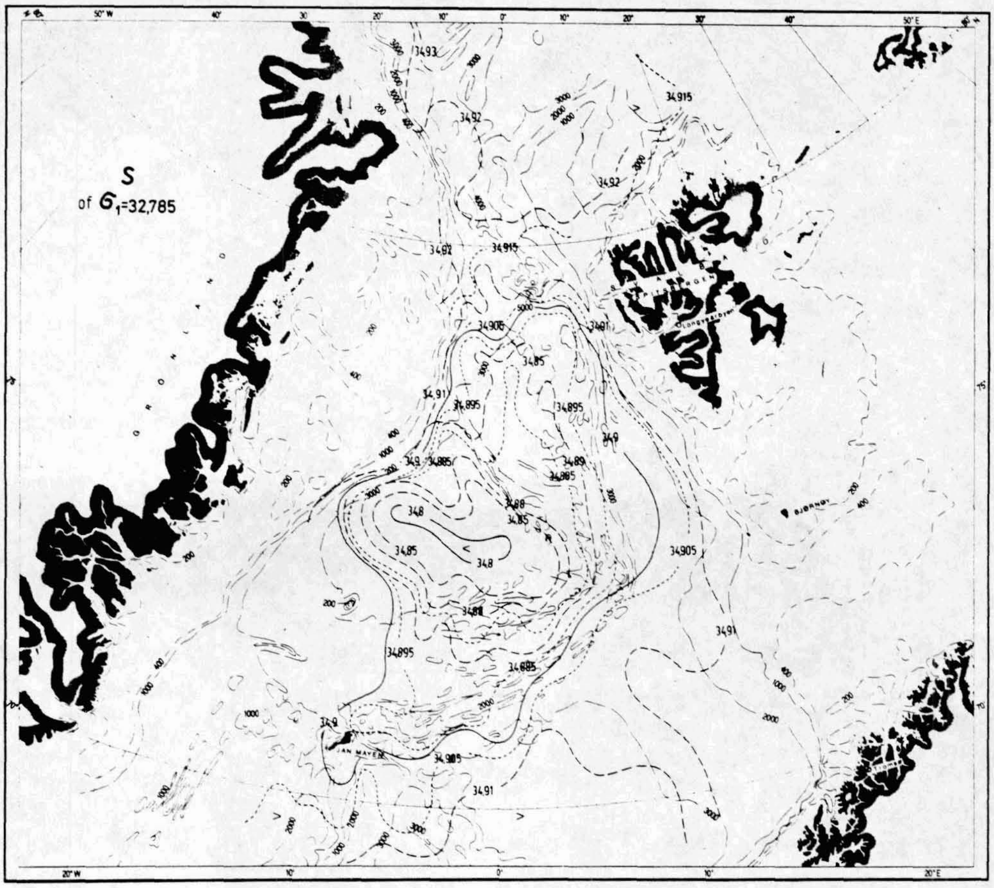

Fig.(3) The distribution of salinity on the isopycnal $\sigma_1 = 32.785$

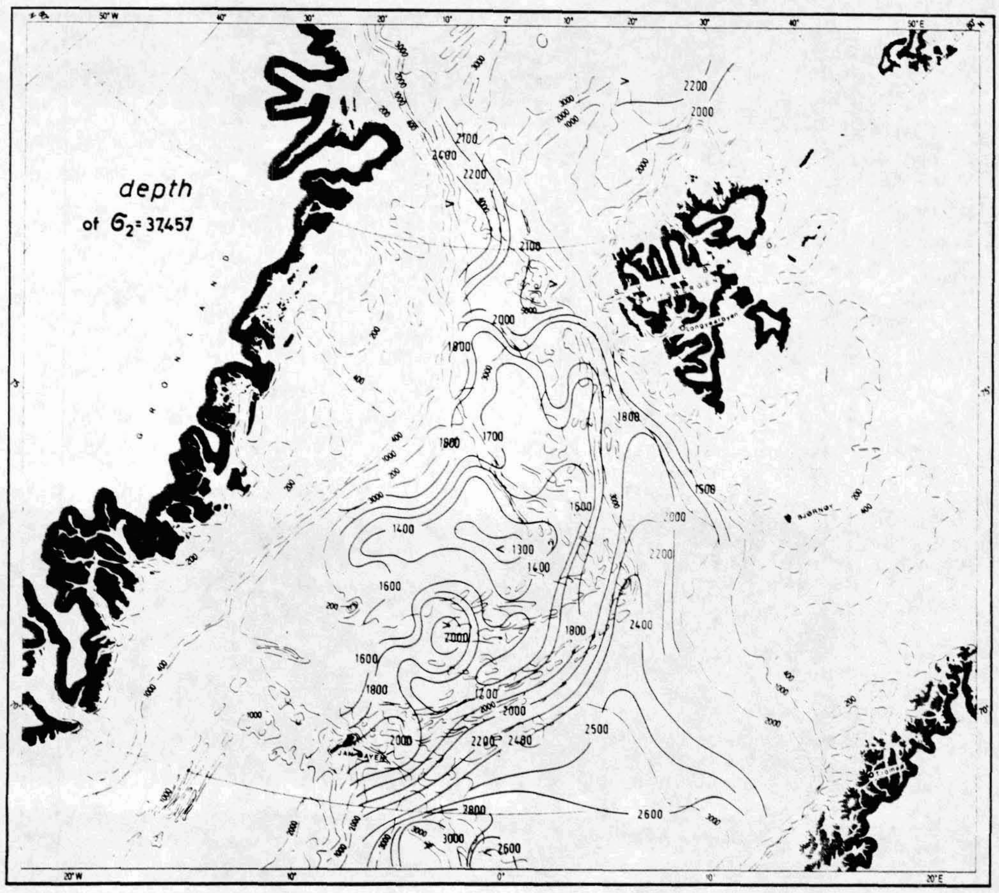

Fig.(4) The depth of the isopycnal $\sigma_2 = 37.457$

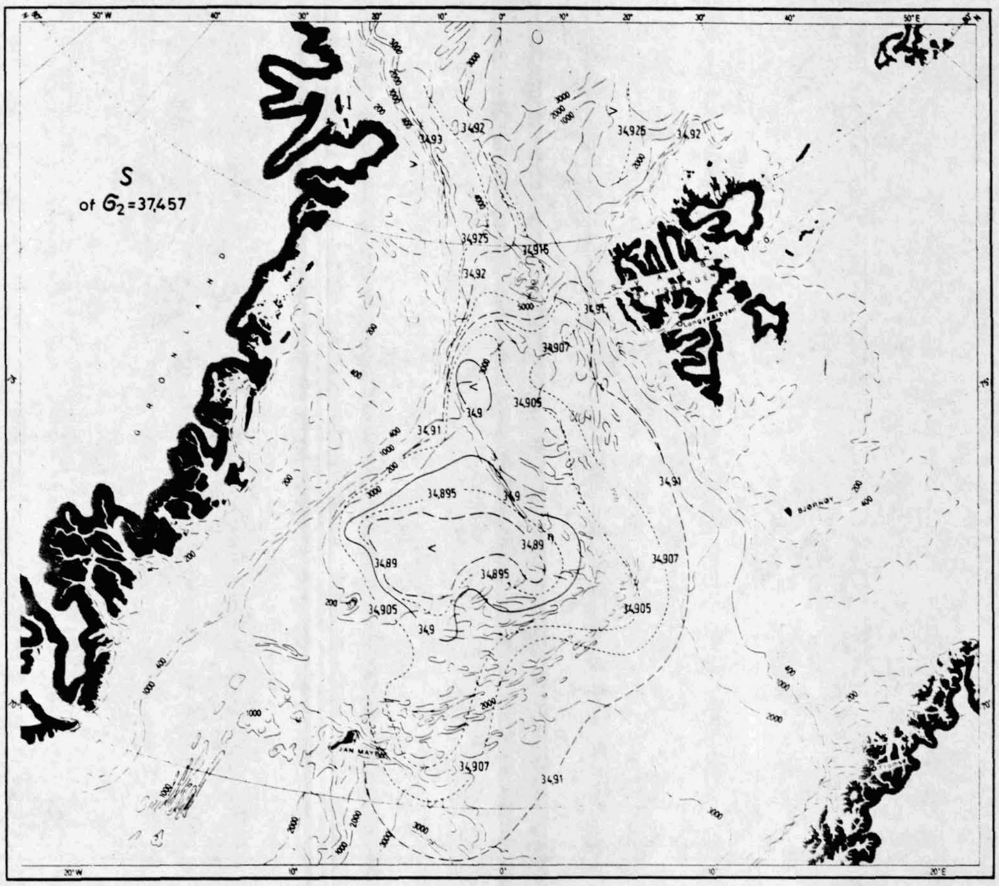

Fig.(5) The distribution of salinity on the isopycnal σ_2 = 37.457

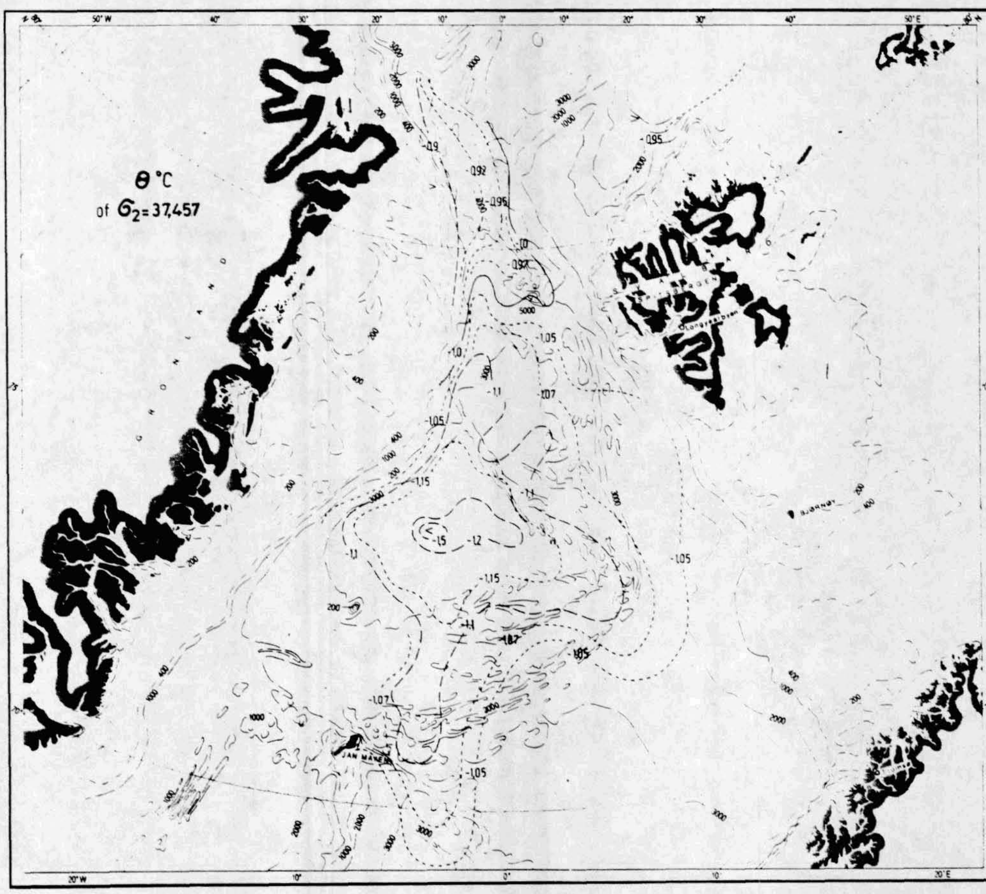

Fig.(6) The distribution of pot. temperature on the isopycnal σ_2 = 37.457

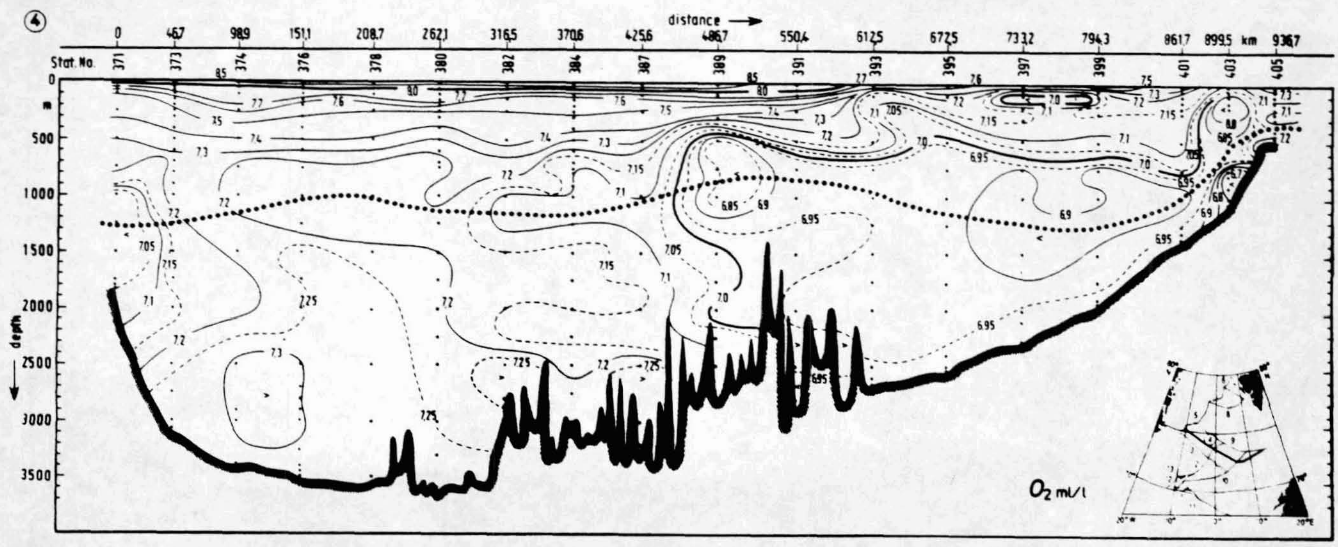

Fig.(7) The concentration of disolved oxygen on a west-east section through the Greenland - Norwegian Seas in May - June 1982. Dotted line marks oxygen minimum

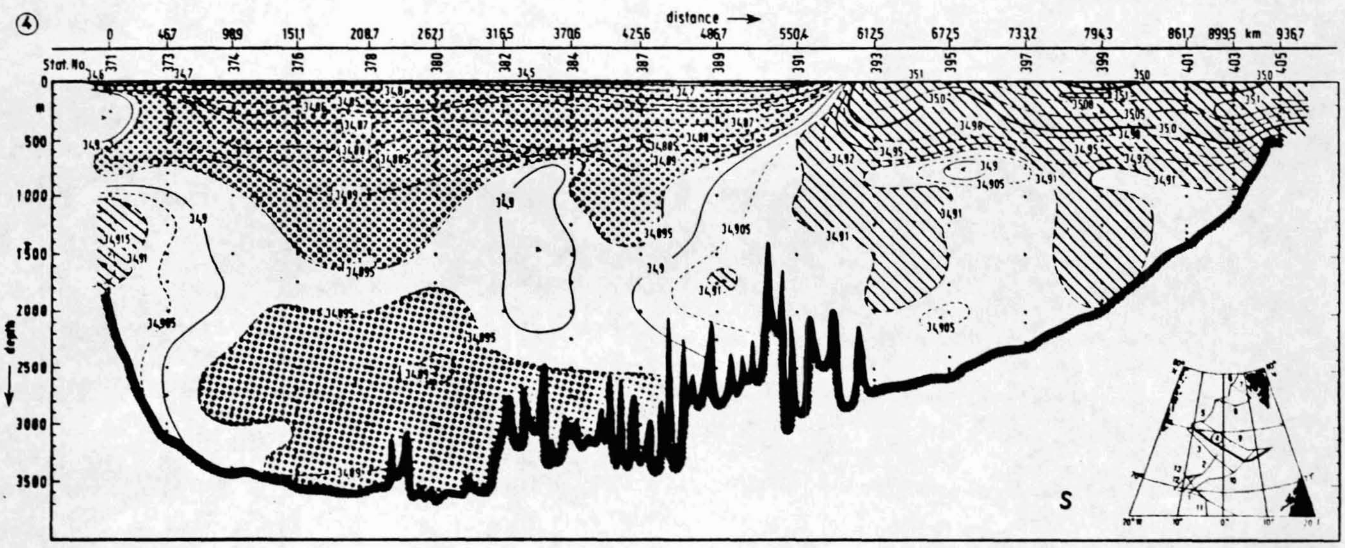

Fig.(8) The distribution of salinmity on a west-east section through the Greenland - Norwegian Seas in May - June 1982. Hatched S > 39.10, dotted S < 34.895

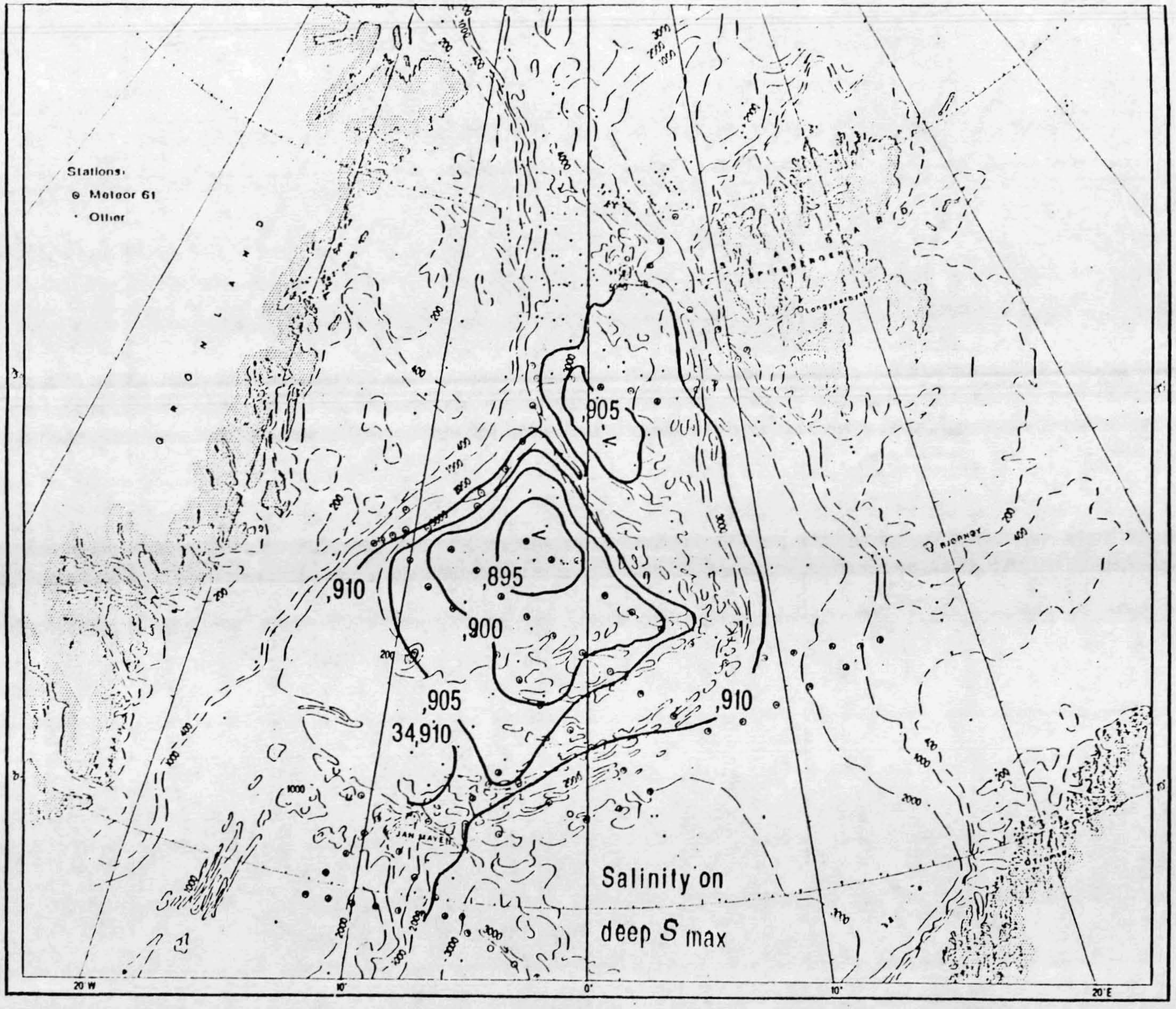

Fig.(9) The distribution of salinity on the Deep Salinity Maximum

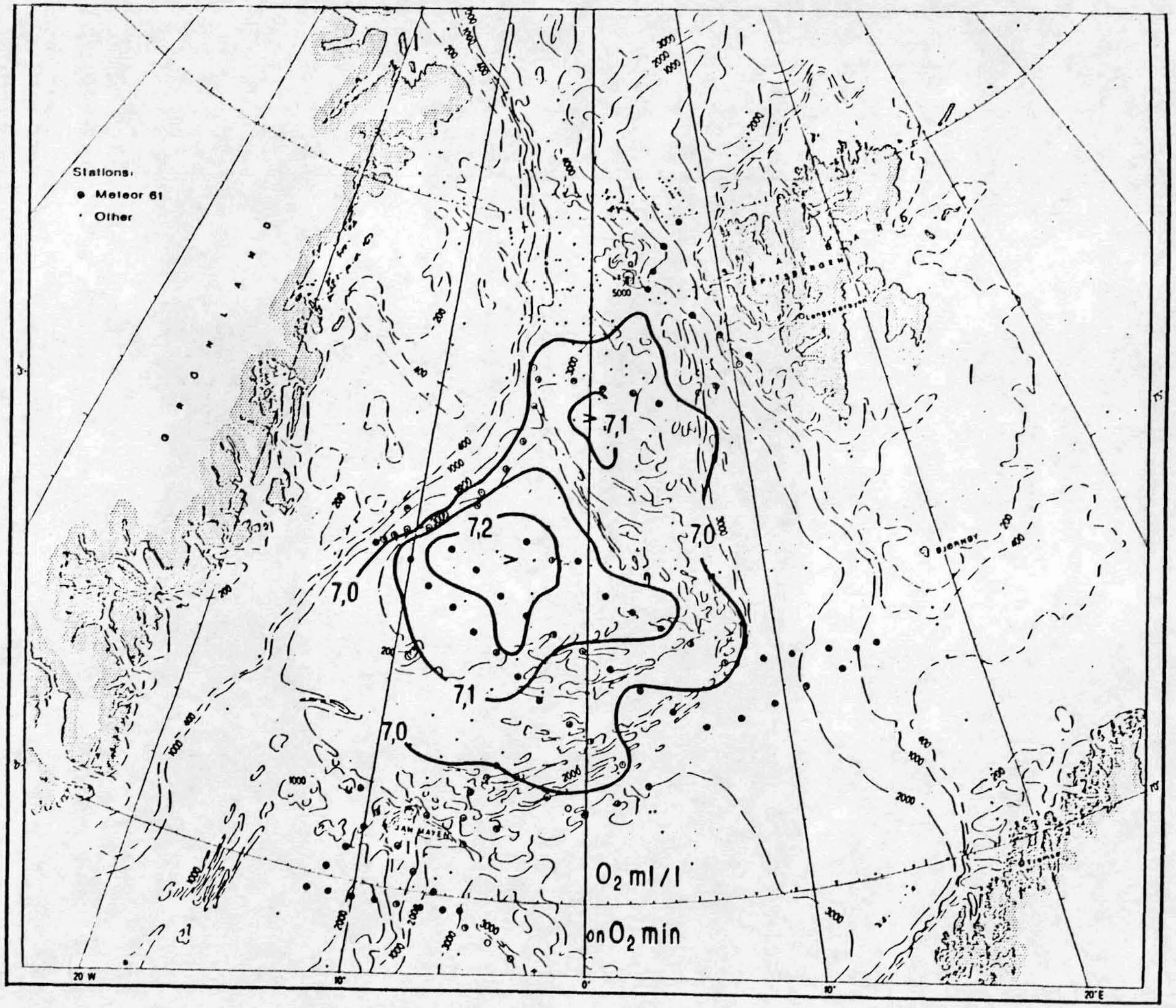

Fig.(10) The distribution of dissolved oxygen on the Deep Oxygen Minimum

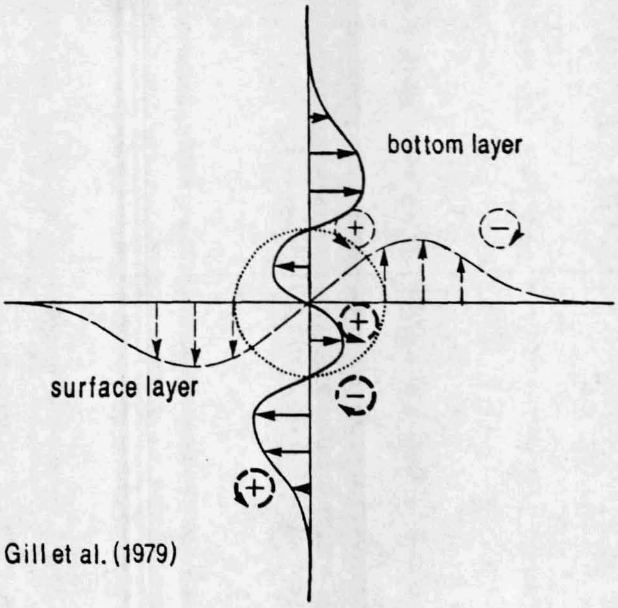

Fig.(11) A conceptual diagram of the two counter-rotating gyres after GILL et al.,1979

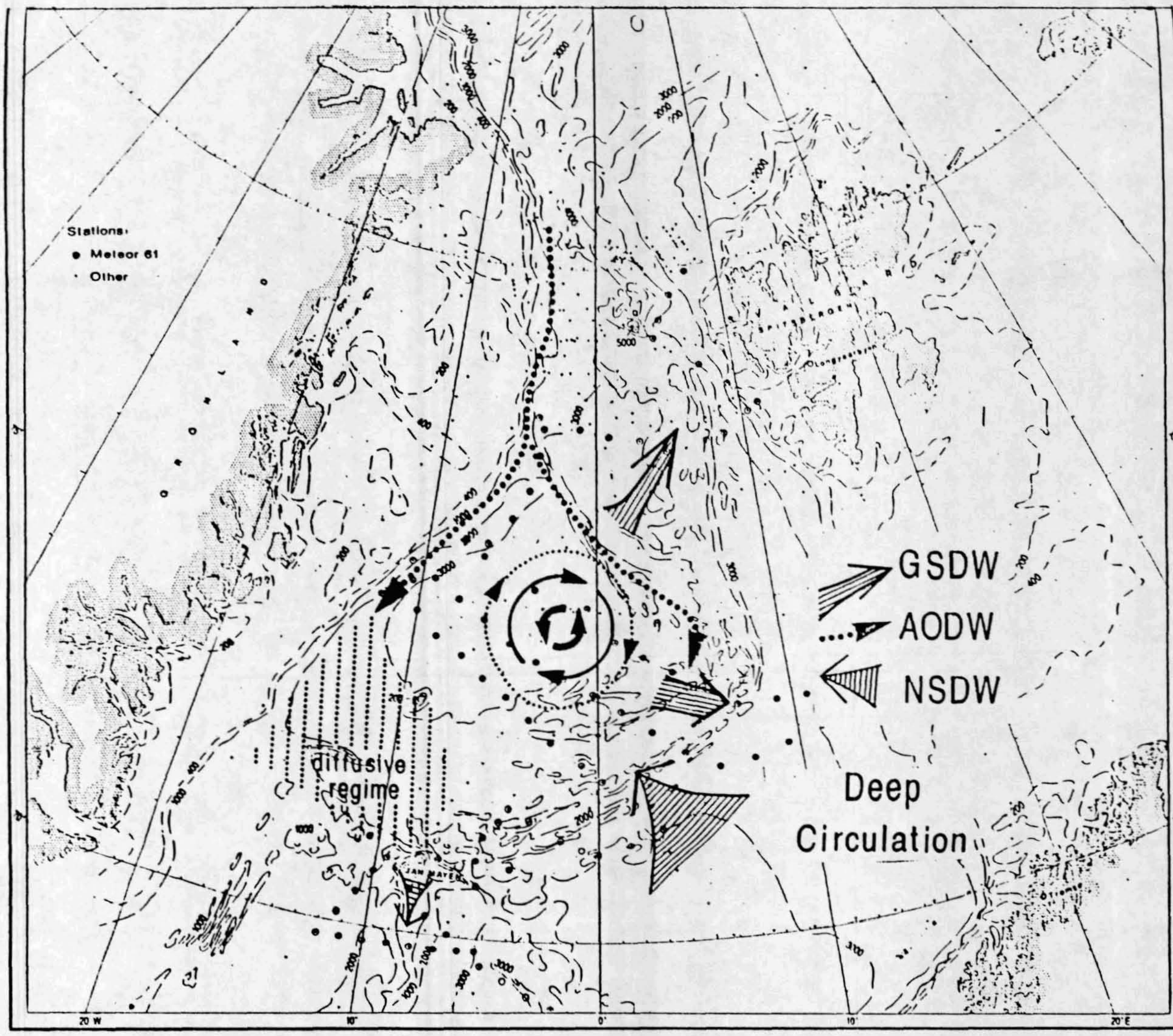

Fig.(12) The deep circulation and the deep anti-cyclonic gyre in the Greenland Sea Basin.
Heavy dots mark Meteor-Stations, light one others.

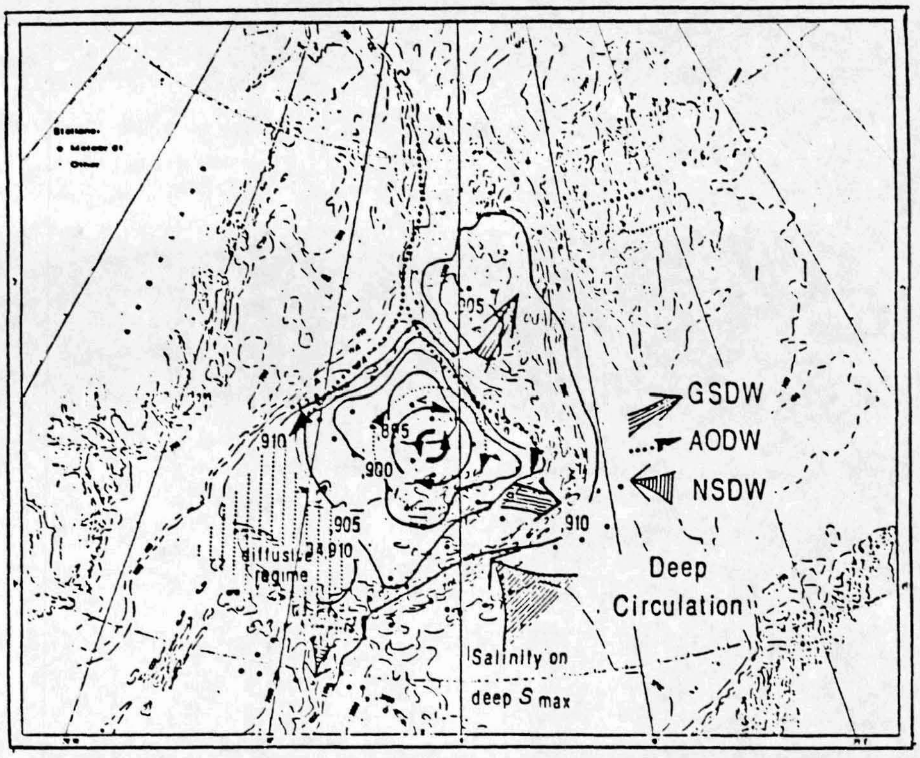

Fig.(13) The deep circulation and the deep anti-cyclonic gyre in the Greenland Sea Basin projected onto the salinity distribution on the Deep Salinity Maximum

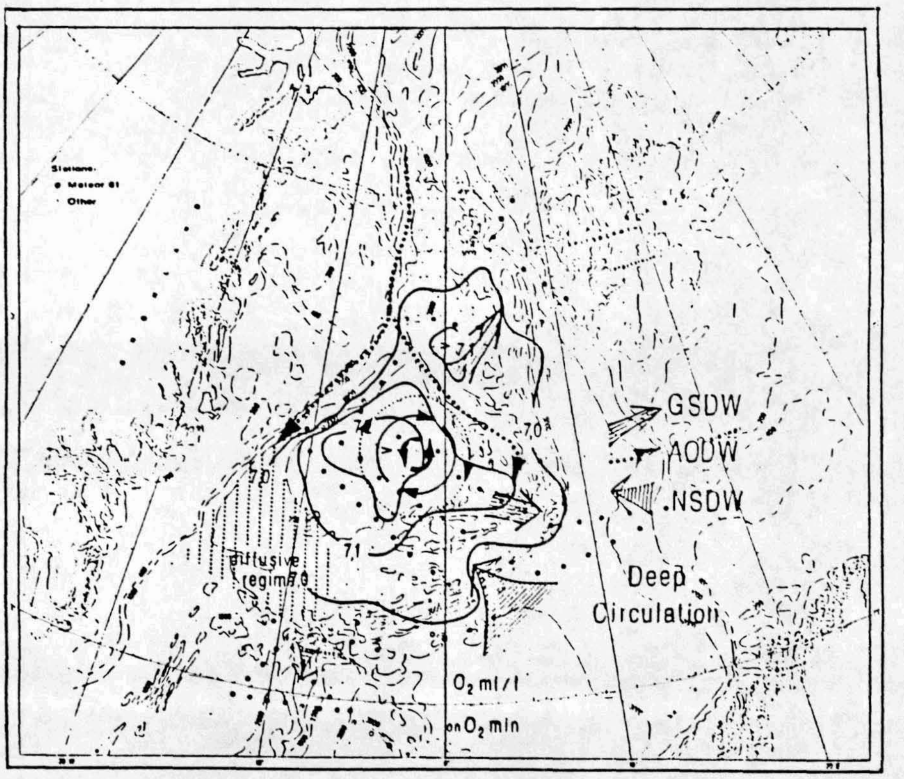

Fig.(14) The deep circulation and the deep anti-cyclonic gyre in the Greenland Sea Basin projected onto the oxygen distribution on the Deep Oxygen Minimum